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ABL Illuminator

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ABL ILLUMINATOR

COIL Illuminator Technology

Schafer's effort in support of the COIL Illuminator consisted of the following task areas:

1. Development of gas laser vision statement;
2. Coordination of contractor and university Raman efforts;
3. Raman analysis;
4. ABL SPO illuminator interface activity;
5. Preparation of briefing comparing gas and solid state laser scaling characteristics; and,
6. COIL CFD workshop support.

1. Gas laser vision statement

Schafer worked in collaboration with Applied Research Associates to prepare a vision statement for the gas laser branch at AFRL. This vision statement began by examining projections made by the New World Vistas study in 1996 for both Air Force mission trends and technology development trends. The New World Vistas vision was embodied by diode-pumped solid state lasers using non-linear optical phase conjugation and fiber optic coupling to achieve energy frugality. Our gas laser vision statement demonstrated that there is an alternate technology pathway to achieve energy frugality using gas lasers. Schafer examined two mission scenarios-threat independent IRCM and cruise missile defense as examples of how gas lasers could achieve energy frugality for missions which require high average power levels in the relatively near future. The accompanying briefing illustrates the logic chain behind this argument (Att. 1).

2. Coordination of Contractor and University Raman Efforts

The COIL illuminator project at AFRL is pursuing two parallel approaches to achieving high efficiency conversion of iodine laser radiation at high average power levels. These are stimulated Raman scattering in molecular gases and Raman scattering in solid-state materials. After an initial survey in 1996-97, Schafer recommended rotational Raman scattering in molecular hydrogen as the best approach using a gas-phase medium. Experiments to validate the theoretical predictions of length and injection seed level, required to achieve conversion efficiencies of 50% or more, are currently being undertaken by STI Optronics. Testing will occur in 1999 using a photolytic iodine laser.

The solid-state Raman scattering approach is not as well defined at this time because of the greater uncertainties in material properties under the high intensity conditions necessary for efficient Raman conversion. Experimental investigations of candidate solid-state Raman materials for the COIL illuminator project are being conducted at Coherent Technologies Incorporated (CTI), the University of New Mexico, and the General Physics Institute in Moscow.

To facilitate progress and coordinate the directions of these various parallel research thrusts, Schafer has held a series of workshops at which the various participants have presented their results. During the present task, these workshops were held on August

18, 1998 and December 1, 1998. Schafer prepared and distributed books of veiwgraphs from each of these workshops.

3. Raman Analysis

Schafer personnel performed analyses of Raman physics issues for the gas-phase Raman converter concept. Schafer resolved a discrepancy in the Raman gain values reported in the literature for stimulated rotational Raman scattering in hydrogen (H_2). This discrepancy was due to a difference of a factor of 3/2 in the Raman gain for circularly polarized pump and Stokes beam in comparison to the case of rectangularly polarized beams. This finding allowed STI Optronics to improve the accuracy of their Raman conversion calculations.

Schafer also performed Raman cell sizing calculations for other gas-phase Raman media candidates, including vibrational scattering in CF4 and SF6 and rotational scattering in H_2, N_2, and O_2. These calculations showed that only H2 offered the possibility of achieving a cell length less than 5-m, which is considered the largest size allowable in the ABL aircraft. The following briefing includes the details of these calculations (Att. 2).

4. ABL SPO Illuminator

Schafer served as an interface between the AFRL COIL Illuminator Project and the ABL SPO. The main areas of emphasis were the baseline performance parameters of the Track Illuminator Laser (TILL), the Beacon Illuminator Laser (BILL), and the component and subsystem weights. The average power and several other parameters of these devices are classified and cannot be reported here. The weights have undergone an evolution as the ABL design baseline has undergone quarterly updates. A significant change occurred in March 1998, when the wavelength of the TILL were changes as a result of adopting Yb:YAG as the baseline (in place of Nd:YAG) and dropping the Raman cell. Current plans are to use Yb:YAG for the TILL and Nd:YAG for the BILL on the PDRR system, then reverse the two laser concepts for the TILL and BILL roles on the ultimate EMD system.

5. Comparison of Gas and Solid State Lasers

Schafer was tasked with preparing a briefing to compare the scaling characteristics of gas and solid-state lasers for medium and high power airborne applications. This briefing began by reviewing previous Air Force experience with Airborne lasers, and how lessons learned from those previous programs has affected subsequent decision making. The briefing then examined how new technologies and the application of the energy frugality concept can reverse some of the negative conclusions previously drawn (Att. 3).

6. COIL CFD Workshop Support

Schafer supported a COIL CFD workshop at Logicon RDA. One purpose of the workshop was to ascertain whether the physics of COIL lasers are accurately modeled by the MINT computer code developed by SRA and used by Logicon RDA. This meeting provided a forum for 37 CFD experts to assess this question, and to make recommendations for reducing the run time of this code.

The following is a summary of the questions and issues which remained unresolved at the close of this COIL CFD Workshop.

1. Is there any possibility of span-wise flow across unit cell boundaries? Related to this was the question of whether periodic boundary conditions are used. It was observed that the unit cell approximation makes the code unable to analyze effects of manufacturing errors and orifice plugging. The further concern was that flow across orifice holes may induce vorticity (turbulence) which is larger than the scale of a unit cell. Even if this vorticity is symmetric on a larger scale, there was a concern that it must be accounted for in order to obtain a correct solution. Related to this was the additional observation that the mesh is very odd looking. Dr. Paul Whalen expressed a concern that there would be enough false vorticity generated by the mesh itself to violate the unit cell assumption.

2. Dr. Wahid Hermina observed that it does not look like the grid on page 4 of the package is fine enough to capture the shear layer in the mixing zone.

3. Professor Steve Orszag expressed concern that vorticity fluctuations might occur which are unmodeled. These could be due to either turbulence or temporal fluctuations in the mass flow rate. Orszag stated that if you have significant streamwise vorticity you can have a major change in the transition Reynolds number (reduction by a factor of 5 is possible.) He pointed out that transition is different than turbulence. Periodic fluctuations could result from localized transition, which is unmodeled by the code. He recommended that AFRL look at temporal frequency spectra measured on RADICL for evidence of fluctuations. It was suggested at this point that Charlie Helms should do some hot-wire measurements in cold flow to look for this behavior.

4. Dr. John Trenholme from Livermore asked if the model included the physics of interaction of the laser beam with condensed water particles. He said that based on his peronal experience, this would be important in that these particles will absorb light no matter what their size. This could present a beam quality issue.

5. Dr. Hermina asked some questions about the degree of chemical equilibrium in the reaction package. He recommended that we compare the collision frequency with the time scales for flow transit through the nozzle.

6. Several people asked if the MINT code uses upwind differencing. Several people had the opinion this would be superior to the central difference technique which is used in MINT.

7. Professor Orszag observed that while the predictor-corrector method is stable in two dimensions, it can be unstable in 3-D. To avoid this instability it is necessary to apply a condition to the maximum time step size. Orszag maintained that implicit methods work fine in two dimensions for avoiding this time step restriction, However he said that if you extend the computations to include 3-D effects you have to restrict the time step size. Someone else observed that you cannot run with an infinite CFL (Courant-Friedrichs-Lewy) number in any implicit method. Professor Orszag asked

if we were really sure that we would not be better off using a fully explicit method for the calculations.

8. It was suggested that we could improve the run time performance of the MINT code by applying sub-cycles to the chemistry calculations. This would involve freezing the fluid dynamics and treating only the chemistry implicitly. The fluid dynamics could be treated explicitly since these phenomena change on a slower time-scale. It would not be necessary to do spatial splitting and speed up can be achieved. However, concern was expressed about getting a disconnect between the density and the energy addition from the chemistry effects. Professor Orszag observed that it would be computationally cheaper to update the density explicitly.

9. Someone asked if the code automatically estimates the discretization error. It was suggested that it would be useful to do this because it would allow us to throw out terms for the next solution or iteration based on the behavior of the previous solution.

10. Several people asked if we had done mesh refinement studies with the code to see if the solution changed as the mesh size was reduced further and further. This is a standard procedure in CFD studies within the NASA community. Charlie Helms observed that when the ROTOCOIL calculations were performed, it was found that the solution changed in going from the coarse grid to the medium grid to the fine grid. This implied that the fine grid was not fine enough and that additional calculations should be done with even smaller mesh sizes to determine the true number of grid points which are required for an accurate solution.

11. Dr. Hermina said that code verification and validation are considered very important items in the Sandia CFD Program. He asked how we do verification and validation with such a large code every time a change is made.

12. Dr. Cliff Rhodes observed that the Cray C-90 computer tells you what percent of the calculations are vectorized. He asked if we had ever looked at this diagnostic which is provided by the computer. The answer was no.

13. Dr. Rhodes also asked how many total hours we would really like to have in a year. An ROM answer was 10K hours per year. Rhodes observed that this is a trivial amount of machine time because people are now measuring problems in hundreds of thousands of node hours per year today. He suggested applying for a Grand Challenge grant through Air Force channels. The Air Force has a panel which allocates these proposals. Capt. Rob Peterkin at AFRL/KAFB is on this body. Information is available at the web site: www.hpcmo.hpc.mil. Dr. Rhodes suggested that if the grant states to the Air Force that it will be supporting a laser weapon program the chances are good that it will be approved. He suggested asking for a 3 year grant.

14. Dr. Mark Christon from Sandia suggested that we could achieve significant improvements and run time by using better guesses to the solution. He specifically

referred to the use of projection-based methods based on Krylov techniques. This involves keeping a series of base vectors which are put on the right hand side of the equations and allows speed up and run time by factors of 5-10. This feature is available in several commercial CFD codes. He said that Sandia sees a difference of 200-300 times in the cost per time step for low Mach number calculations. He recommended that we talk to Dr. Phil Gresho at Sandia about these projection methods.

15. When finite element methods (FEM) were discussed as a possibility for reducing run time, Alan Lampson stated that the communications requirements were uncertain with this technique. Someone asked why he thought communications times were uncertain for FEM codes. He said that typically people pre-compute the communications paths and that this part of the problem is very deterministic. However, he said that we should not try to do this ourselves. We should arrange a mind-dump from people who have done this with FEM codes.

16. Several people asked if we are totally married to the ADI (Alternating Direction Implicit) solver approach. The ADI technique has a problem with parallel computing architectures. As you break up the problem into more blocks you lose the implicit aspects of the algorithm across the processors.

17. Dr. Hermina said that Sandia is using domain decomposition techniques extensively for time accurate solutions. He asked if we are concerned with time accurate behavior capability in our calculations. Although the answer is no for the present type of calclulations, it was observed that maybe we should be for super-sonic injection configurations. In particular, it might be possible that oscillatory behavior will occur with the supersonic injection orifices. Tim Madden said that he investigated this for his PhD thesis with a high resolution grid and did indeed pick up an unsteady mode around the subsonic injection holes of the RADICL device.

18. Several people in the audience expressed concern that we were not using enough grid points. One person stated that if you have too few grid points, you can get smoothing of gradients with more grid points. The solution can oscillate back and forth from one point to another.

19. Several people asked if anyone had done a comparison of GASP and MINT (or any other state-of-the-art commercial codes) for non-reacting flows. This was suggested as an easy way to get a comparison of the basic speed and run-time behavior of these codes in a short time.

20. It was suggested that we investigate the potential of using features of the AZTEC distributed memory parallel solver. It employs unstructured grid, along with variable block storage and conjugate gradient techniques. It would give an idea of what is to be gained by getting rid of the ADI solver in the MINT code. It was estimated that this might take 4-5 man months to accomplish. As a preliminary it was suggested that we download AZTEC from the web.

21. Someone else observed that there is some evidence in the literature that Newton schemes don't work well for large velocity shears. They wondered if the MINT code's use of a Newton iteration might be responsible for its slow convergence characteristics.

22. It was observed that the hypersonics community is not putting all of its eggs into one basket and focussing on a single computer code. They are sponsoring the development and use of several codes and actively doing code to code comparisons to assess the behavior of the various methods available and to determine which ones are best for which problems.

LASER MISSIONS 2020

An AFRL/DEL Analysis

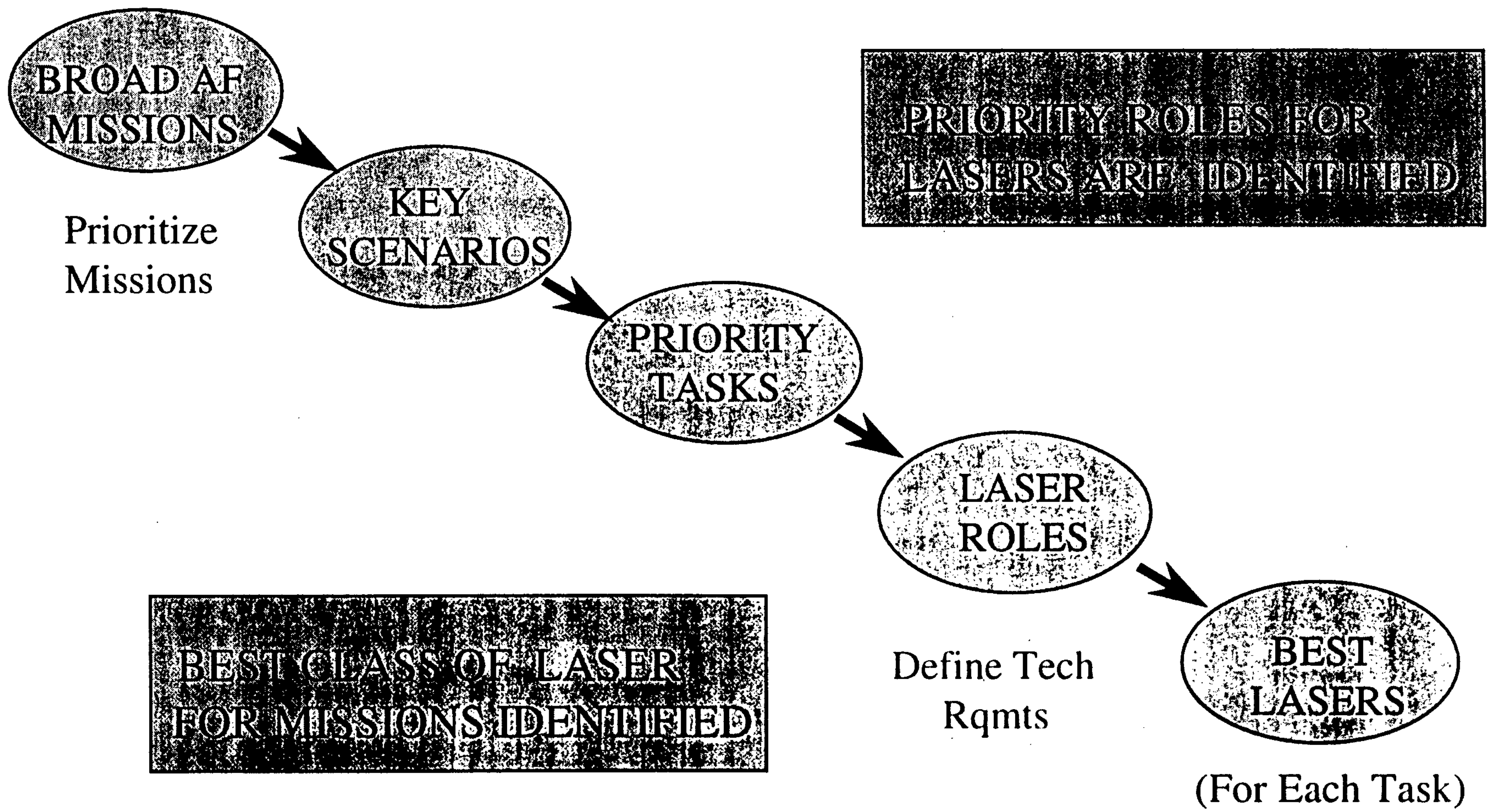
STUDY OBJECTIVES

- IDENTIFY HIGH-PAYOFF AF MISSIONS FOR LASERS FOR THE NEXT FEW DECADES
- IDENTIFY THE MOST APPROPRIATE CLASS OF LASER FOR EACH OF THESE MISSIONS

STUDY REFERENCES

- New World Vistas
- Laser Mission Study
- Adjunct Mission Studies
- Future War--Aerospace Campaigns
- Laser 21

LASER STUDY METHODOLOGY



PRIORITY MISSIONS

- Cruise Missile Defense
- Aircraft Self-Protection
- Space Control
- SEAD-- UAV Optical Weapon
- Counterproliferation Sensor
- Base Defense (Force Protection)
- Battlefield Illuminator Applications
- Global Precision Optical Weapon
- EOD Disposal

THREAT-INDEPENDENT IRCM

- Scenario: Missile of unknown type engaged 5 km from C-17
  May be RF, IR, or beam rider
- Solution: HEL on A/C for self-protection and escort defense
- A top-level laser system concept:

+Wavelength, um	1	1
+Aperture, cm	10	20
+Jitter, ur	10	10
+Power, kW	400	150

Figures of Merit

- Cost
- λ, λ agility
- Weight
- Volume
- Efficiency
- Beam quality
- Temporal format
- Peak power
- Safety and environmental thermal management
- Number of targets engaged

Evolution of Airborne Laser Self Defense

- 1975-77: SRAT Program undertaken to develop bomber self-defense laser (CO_2 EDL, GDL)
- 1978: HELTAS study suggests semi-active radar guided missile will become dominant threat by mid-1980's (IR missiles handled by other means or go away)
- 1979: CW CO_2 GDL canceled; RP CO_2 EDL adopted for JSRT because of better perceived penetration of multi-ply radomes
- 1980: USAF CO_2 program canceled to emphasize strategic missions; pulsed DF retained for anti-radar missile defense
- 1982: Pulsed DF canceled.

Better focusability and lower atmospheric absorption at COIL wavelength, as well as reduced mirror train losses, can significantly increase intensity on target, enabling engagement of several missiles.

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Evolution of Airborne Laser Self Defense

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1998 Retrospect:
- The IR missile threat has not gone away
- The U.S. still has no defense against IR or radar guided missiles

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What Needs To Be Done for Tactical Aircraft DEW?

- Update HELSLED algorithms for systems of interest
  - New laser concepts
  - Advanced component technology
  - New beam control technologies
  - Weight/volume scaling
- New point designs & concept definition
  - New platforms (e.g. UAV's)
  - Reduced target ranges
  - Energy frugal kill concepts

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CO Overtone Laser Concept Development

- Requirements flowdown from target susceptibility data
- Point design optimization & trade study
  - Supersonic expansion cooling, RF discharge pumping
  - Cryogenic cooled waveguide pumping
  - Room temperature discharge
- Fundamental suppression
  - Coatings
  - Absorption cell
- Platform integration study
  - Fighter & transport
  - MEA accomodation
  - Pressure recovery/exhaust management
- Beam control system definition
  - Fiber coupling & transmission
  - Propagation analysis
  - Conventional vs. conformal beam forming

THE MESSAGE

Recent Data on SOA of COIL and DPSSL*

Clear Mission Needs For High Power Lasers Having Good BQ**

Multiple Tech Options Needed for Meeting Difficult Future Requirements

A Vigorous Program in Advanced Gas and Chemical Lasers Must be Maintained in AFRL/DEL

*ABL and ATLAS Reports

**New World Vistas and other Studies

Raman Status Update

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Liquid Raman Shifters: Are They Feasible?

- Some liquids exhibit high Raman conversion efficiencies and wavelength shifts in the range of interest
- →Why not use liquids as Raman media?
- In most liquids, the intensity threshold for self-focusing is smaller than that for SRS
- Self-focusing is then the primary nonlinear process

  --Beam breakup→poor beam quality

  --Secondary stimulated scattering processes→poor conversion efficiency
- Implications for solid-state SRS?

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Optical Configurations for SRS

- External Cavity Cell
  --Conventional geometry for large scale Raman amplifiers
  --Requires beam compacting between pump and cell
  --Easy to implement stokes seed injection
- Intracavity Cell
  --Higher intensity than external cell
  →Higher Raman gain
  --Stokes seed injection impractical
  --More difficult to control buildup of stokes and parasitic waves (buildup from noise)

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Rayleigh Range Criterion

- The pump beam must be focused and collimated prior to entering the Raman amplifier
- The Rayleigh range of the collimated beam must exceed minimum required Raman cell length
- Rayleigh range= $Z_R = \frac{\pi w^2}{\lambda} = \frac{4P}{\lambda I}$
- For P=1 MW (1J@1μs)-RADICL Prediction

I (MW/cm^2)	Z_R (cm)	L_{MIN} (H_2 ROT) (cm)
50	608	523
100	304	261
200	152	130
300	101	87

Note: Z_R and L_{MIN} both scale linearly as I^{-1}

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Comparison of RADICL and FLM

Rayleigh Range$=Z_R = \frac{\pi w^2}{\lambda} = \frac{4P}{\lambda I}$

RADICL: P=1MW

I (MW/cm^2)	Z_R (cm)	L_{MIN} (H_2 ROT) (cm)
50	608	523
100	304	261
200	152	130
300	101	87

FLM: P=8MW

I (MW/cm^2)	Z_R (cm)	L_{MIN} (H_2 ROT) (cm)
50	4867	523
100	2433	261
200	1216	130
300	811	87

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Minimum Raman Cell Length for 50% Conversion

$$L_{MIN} = \frac{1}{gI}\left[\ln\left(\frac{\eta}{1-\eta}\right) - \ln r\right]$$

(Assume I=60MW/cm^2)

	λ_s (μm)	g (cm/w)	L_{MIN} ($r=10^{-4}$)	L_{MIN} ($r = 10^{-2}$)
H_2 (ROT)	1.425	4.1×10^{-10}	4.4 m	2.5 m
$2\times H_2$ (ROT)	1.557	4.1×10^{-10}	8.8 m	5.0 m
N_2 (ROT)	1.328	2.15×10^{-12}	560 m	320 m
O_2 (ROT)	1.328	5.7×10^{-13}	3070 m	1730 m
CF_4 (VIB)	1.49	2.9×10^{-12}	610 m	350 m
SF_6 (VIB)	1.46	5.0×10^{-12}	360 m	200 m

CONCLUSION: Hydrogen is the only gas-phase Raman shift candidate which can be packaged in an external cavity cell.

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Raman Gain Summary at 1.315 Microns

	$\Delta\nu_R$ (cm^{-1})	λ_S (μm)	g (cm/w)
H_2 (ROT)	587	1.425	4.1×10^{-10}
N_2 (ROT)	75	1.328	3.15×10^{-12}
O_2 (ROT)	71	1.328	5.7×10^{-13}
CF_4 (VIB)	908	1.49	2.9×10^{-12}
SF_6 (VIB)	775	1.46	5.0×10^{-12}

NOTE: Gains are for opposite circular polarizations on pump and stokes beams (maximum gain case for rotational SRS) and linear parallel polarizations (maximum gain case for vibrational SRS).

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Effect of Parasitic Processes

- Anti-stokes line can be generated via four-wave mixing
- Criterion for avoiding anti-stokes generation:
  Keep the angle between pump and stokes, and the beam divergence of pump and injected stokes beams, less than $\beta/10$, where

$$\cos\beta = \frac{\left(\frac{n_s}{\lambda_s}\right)^2 + \left(\frac{2n_p}{\lambda_s}\right)^2 - \left(\frac{n_a}{\lambda_a}\right)^2}{4\frac{n_s}{\lambda_s}\frac{n_p}{\lambda_p}}$$

Stokes: $n_s = 1 + 1.27 \times 10^{-4}\left(1 + \frac{\nu_s^2}{\nu_0^2}\right)\rho$

Pump: $n_p = 1 + 1.27 \times 10^{-4}\left(1 + \frac{\nu_p^2}{\nu_o^2}\right)\rho$

Anti-Stokes: $n_a = 1 + 1.27 \times 10^{-4}\left(1 + \frac{\nu_a^2}{\nu_o^2}\right)\rho$

Schafer Selection Rules for Raman Scattering

- Rotational Raman scattering
  --Vibrational quantum number:
  $\Delta v=0$
  --Rotational quantum number:
  $\Delta J=0, \pm 2$
  --Only $\Delta J=+2$ transitions contribute to positive gain
- Vibrational Raman scattering
  --Vibrational quantum number:
  $\Delta v=\pm 1$
  --Rotational quantum number:
  $\Delta J=0$

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Rotational Raman Gain Coefficient

$$\mathbf{g_s} = \frac{2\lambda_s^3 \Delta N_J}{hc\pi\Delta\nu} \frac{\partial\sigma}{\partial\Omega}$$

Only ΔJ=+2 contributes to positive gain

$$\frac{\Delta N_J}{N} = \frac{\sum_{T_J}(2T_J+1)(2J+1)}{Q_{RT}(T)}\left\{\exp\left[-\frac{hcB}{k_B T}J(J+1)\right] - \exp\left[-\frac{hcB}{k_B T}(J+2)(J+3)\right]\right\}$$

Where $Q_{RT} = \sum_{J,T_J}(2T_J+1)(2J+1)\exp\left[-\frac{hcB}{k_B T}J(J+1)\right]$

T_J=Molecular nuclear spin

$$\frac{\partial\sigma}{\partial\Omega} = \frac{2}{15}\frac{2\pi\gamma_s^4}{C}\frac{(2J+1)(J+2)}{(2J+1)(2J+3)}\alpha_{oo}$$

Where α_{oo}=Ground state anisotropic polarizability

WJSA

COIL ILLUMINATOR TECH BASELINE: COIL ABL WEIGHT MODEL

- ***IN 1993, WJSA DEVELOPED WEIGHT SCALING MODELS FOR FOUR LEVELS OF COIL ABL TECHNOLOGY***
- ***TWO ARE MOST RELEVANT FOR COIL ILLUMINATOR ANALYSIS:***
  - CASE (3): NEAR-TERM LIGHTWEIGHTING
    - » COMPOSITE TUDOG GENERATOR
    - » SINGLE-STAGE EJECTOR
    - » 10:1 PRIMARY HELIUM/CHLORINE RATIO
    - » 10M TO 2M BDP DEPLETION
  - CASE (4): FAR-TERM LIGHTWEIGHTING
    - » INCREASED THROUGHPUT GENERATOR
    - » INCREASED EXTRACTION EFFICIENCY
    - » SUPERSONIC-SUPERSONIC EJECTOR
- ***RECOMMEND MODIFIED CASE (3) FOR ILLUMINATOR STUDIES***

Tactical Airborne Directed Energy

- Tactical laser development history
- Why tactical airborne DE Now?
- Possible airborne DE missions/tasks
- Technological advances enabling for tactical airborne directed energy
- Where do we go from here?

Tactical Laser Development History

(Key AF Milestones)

- Tri-Service Laser (TSL)
  - initiated in 1969, laser delivered in 1971, F-4 lethality tests in 1976
- Airborne Laser Laboratory
  - initiated in 1972, drone lethality tests in 1973
- Weapons Lab CO_2 tactical laser programs cancelled - 1980
  - CW and pulsed CO_2 systems judged ineffective against RF missile threat and IR missiles not considered high threat
  - pulsed DF program retained for anti-radar missile defense
  - emphasis shifted to strategic DE programs
- Pulsed DF program cancelled - 1982

Tactical Laser Development History
(Key AF Milestones, continued)

- Army Forward Army Laser Weapon Demo program - cancelled in 1982
  - part of Close Combat Laser Anti-Aircraft Weapon program
  - perceived vulnerability of laser system to Soviet threat - (not able to defend itself against saturation attacks)
- Successful demo of tracking & laser destruction of Katyusha - 1996
  - Nautilus demo used MIRACL and SEA-LITE beam director

Why Tactical Airborne DE Now?

- US forces drastically reduced in size: must use economy of force and increased tempo of operations to magnify impact of smaller numbers of combatants
  - speed-of-light delivery allows immediate concentration of combat power at decisive times and places
  - more accurate target selection and more efficient use of conventional or DE weapon resources
- Tactical directed energy needs dominant in current world politics
  - many tasks fall under "operations other than war"
  - police actions require careful adherence to rules of engagement - directed energy allows graduated responses

Why Tactical Airborne DE Now?

- Airborne basing makes effective use of inherent DE advantages
  - system mobility allows attack of multiple, dispersed targets and rapid movement to other locations
  - mobile platform makes enemy countermeasures more difficult
  - magazine limited only by fuel on board
  - higher vantage point allows wide area of coverage using advanced optical surveillance and targeting systems
  - laser propagation improved when above majority of aerosols
- AF will probably function more often in mode of AEF - rapid deployment, limited footprint, protecting forces at remote site, etc

Possible Airborne DE Missions/Tasks

- IR Counter Measures - DJ and D2
- Cruise missile detect and destroy (UAVs and manned A/C)
- Underground structure location
- Counterair - Deny, Degrade, Damage, Destroy
  - intimidation, disorientation, radar/electronics upsets, fuel system failure, structural damage
- Target ID and selection
- Target designation
- Ballistic winds
- Gunship for ground operations support (search and rescue, special operations insertions, area denial, etc)

Possible Airborne DE Missions/Tasks

- SEAD (radars, AA, FLIR adjunct targeting systems, etc)
- Laser comm: air-to-air
- Laser comm: air-to-space
- Fleet defense from anti-ship cruise missiles
- Detection of CW/BW agents (and drug manufacturing sites)
- Point and ground area defense (e.g. Golan Heights) from TBMs and artillery
- Counter-battery
- Psyops - intimidation, tactical deception

Technological Advances Enabling for Tactical Airborne Directed Energy

- Non-linear optics
  - gas and solid-state Raman wavelength shifting (efficiencies of 50% achieved routinely, multi-kW conversion promising)
  - four-wave mixing demonstrated with CO_2 at 40 kW avg
- Optical system components
  - hi-reflectivity coatings and resulting uncooled optics
  - non-mechanical beam steering
  - gradient index optical materials (enabling conformal optics)
  - mode-maintaining, low-loss fiber optics delivery techniques
  - fiber-coupled laser arrays
  - phase matching using piezo actuators on fibers (in progress)
- Augmented prime power on aircraft - Mega Watts by 2012

Technological Advances Enabling for Tactical Airborne Directed Energy

- Compact pulse power components: capacitors, solid state switches (IGBTs), fly wheel energy storage
- Beam control
  - high-power adaptive optics techniques
  - MEMs technologies reduce size and complexity of components, enabling AO use in compact tactical applications
- Extremely short pulse lasers and novel effects
- Thermal management - microchannel cooling, heat pipes, etc
- Compact, flight-qualified diode lasers, fiber lasers, and DPSSLs (at relatively low and medium average powers, to date)
- Compact, high average power, mid-IR electric lasers: CO, CO overtone, Discharge Oxygen-Iodine Laser (DOIL)

Where do we go from here?

- There are many current, high-priority missions/tasks that can be best done using tactical airborne directed energy
- Some of these missions can be met, to some level, using current laser technologies
- An aircraft with the capabilities envisioned for a FotoFighter would revolutionize our ability to carry out the wide variety of battles, police actions, and nation-building that are being demanded
- We cannot afford to wait 30 years for a FotoFighter!
  - We must design a program that explores near-term options while investing in long-range, high-payoff technologies
  - We must design such a system to allow incorporation of new technological capabilities as they become available

Where do we go from here?

- Develop non-mechanical beam-steering techniques and hardware
- Develop gradient index materials that can be coupled with non-mechanical beam steering, allowing conformal output apertures
- Develop low-loss fiber delivery techniques and hardware for several key wavelengths and which preserve high beam quality in transmitting beams to aircraft output apertures
- Develop wavelength conversion techniques such as gas and solid-state Raman conversion, to maximize efficiency and fieldability and minimize complexity of fiber systems on aircraft
- Develop integrated aircraft fiber optic flight-control systems and delivery systems for laser energy and sensory data
- Develop methods to phase lock outputs from fiber bundles, perhaps using piezo-electric actuators imbedded in fibers

Where do we go from here?

- Develop laser diodes, coherent diode arrays, diode-pumped solid state lasers, diode-pumped gas cells, and fiber lasers for current medium power applications and future high average power systems
- Develop electric discharge gas lasers for current high average power applications that capitalize on near-term MEA program
    - CO and CO overtone - currently being explored
    - DOIL - no current work
        - Electric Discharge Singlet Oxygen Generator (EDSOG) system analysis done in 1994 for PL
        - Rocketdyne supported initial investigation of EDSOG, but funding was insufficient to accurately measure $^1\Delta$ yield
        - No further work: did not seem to offer order of magnitude improvement over existing chemical approach

What is an electric discharge SOG?

- $e^- + O_2 \dashrightarrow O_2(^1\Delta)$
- Process has been studied since mid-1970s
- Unusual electric discharge conditions required for high performance
  - requires multiple sequence of "poker" pulses every few μsec
  - "poker" pulses generated by high voltage avalanche pulser
- Yield estimated during initial experiments: ranges from 19 to 30%
- An EDSOG would eliminate weight of BHP in comparable COIL
- Thermal management system would be simplified since heat exchanger would operate at 400-600 K, rather than 250 K, greatly increasing heat transfer rates and reducing system size
- No hazardous chemicals are used
- No water vapor is produced, so there are no $^1\Delta$ transport losses

What does DOIL offer for FotoFighter?

- Continuous operation, using available aircraft power
- Compact system: if yield is actually 19%, 30kW system feasible for tactical aircraft; if yield is 30%, 500 kW- 1MW system is possible
- Closed cycle operation
- Laser system not susceptible to g-loading problems
- Low-loss fiber delivery to convenient apertures on aircraft
    - will allow development of mode-maintaining fiber hardware
- High-efficiency (50%) Raman conversion to convenient wavelengths (1.5 μm conversion demonstrated, power scaling predicted)
    - required conversion could be done near apertures
- Simultaneous lasing on multiple electronic transitions possible using magnetic splitting of electronic levels - beat frequency target effects

What should be done now?

- Improve computational model of electric discharge generation of $^1\Delta$ oxygen to include other processes
  - Refine design of “poker” pulses to optimize discharge parameters for operation at higher system pressures
  - Confirm accuracy of model results with Dr Alan Garscadden
- Obtain advice from Maj Gen (Ret) Don Lamberson and SAB
- Develop initial model of DOIL system for aircraft integration
- Modify existing EDSOG device for high pressure operation and optimal “poker” pulses
- Experimentally measure yield of EDSOG to determine if DOIL could produce tens of kilowatts or Megawatts
- If results promising, develop roadmap for DOIL technology development by AF, with possible support from other Services and industrial groups interested in long run time, fiber-delivered operations